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Use of mobile applications for determining the leaf area of cotton plants

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ABSTRACT: The objective of this study was to analyze leaf area data for four cotton cultivars estimated using the Petiole and LeafArea software, with leaf area calculated as the product of leaf length, leaf width, and a correction factor, and the LI-COR device method used as the standard for validation. The validation of the data estimated by the Petiole software and LeafArea, and the method by which leaf length and width correlate, was performed using statistical indices to evaluate precision and accuracy. The petiole showed the best performance in estimating leaf area for the cultivars TMG44B2RF, IMA5801B2RF, and FM985GLTP. The methodology using leaf dimension measurements and a correction factor is more effective for estimating the leaf area of cultivar BASF – FM 944GL. Among all the evaluated methods, the LeafArea method had the lowest effect on the leaf area of the cotton cultivars. The methodologies evaluated provide precise and accurate estimates of leaf area for the different cotton cultivars, with results that vary across cultivars.
Keywords: leaf morphometry; digital photography; *Gossypium hirsutum* L.; image processing.

Uso de aplicativos para determinação da área foliar do algodoeiro

RESUMO: O objetivo desse estudo foi analisar os dados de área foliar de quatro cultivares de algodão estimados pelos softwares Petiole e LeafArea e, com dados obtidos com o produto de comprimento e largura da folha e um fator de correção, utilizar o aparelho LI-COR como método padrão para validação dos demais. A validação dos dados estimados pelos softwares Petiole e LeafArea e da metodologia que correlaciona comprimento e largura da folha foi realizada com o auxílio de índices estatísticos, que avaliaram a precisão e a exatidão. O aplicativo Petiole apresenta o melhor desempenho na estimativa da área foliar das cultivares TMG44B2RF, IMA5801B2RF e FM985GLTP. A metodologia que utiliza as medidas das dimensões das folhas e um fator de correção é mais eficaz na estimativa da área foliar da cultivar BASF – FM 944GL. A estimativa da área foliar obtida pelo aplicativo LeafArea apresenta a menor eficiência entre todas as metodologias avaliadas nas cultivares do algodoeiro. As metodologias avaliadas fornecem estimativas precisas da área foliar das diferentes cultivares de algodoeiro, com resultados que variam entre si.
Palavras-chave: morfometria foliar; fotografia digital; *Gossypium hirsutum* L.; processamento de imagem.

1. INTRODUCTION

Leaf area is crucial for photosynthetic efficiency, detection of biotic and abiotic damage, growth analysis, plant metabolism, final crop production, quality, and maturation, as well as for anticipating physiological responses at the plant level (PINHEIRO et al., 2020; TAIZ et al., 2021). In addition, it aids in intercepting solar radiation, which, under appropriate conditions of temperature and water availability, increases the production of photoassimilates used in flowering and influences productivity (LIU et al., 2017; SABOURI; SAJADI, 2022).

In this sense, leaf area can be quantified using several methods, both destructive and non-destructive. Salazar et al. (2018) and Taiz et al. (2021) reported that the destructive methods are those called direct, with the use of a tape measure, measured in the field or in a protected environment that needs to remove the leaf from the mother plant; nondestructive, i.e., indirect, methods use instruments that do not need to remove the leaf from the mother plant (PINHEIRO et al., 2020; ZHANG, 2020).

The use of different methods for leaf area analysis, such as the LeafArea and Petiole applications and the LI-COR model 3100, is essential. The LI-COR model 3100 is considered the reference method, offering distinct advantages, such as practicality, accessibility, precision and reliability, allowing a comparative and comprehensive evaluation of leaf area. This finding corroborates the results of studies by Meira et al. (2020), who used accurate leaf area measurements via software and compared them with those obtained via the electronic method (LI-3100). The combination of the LI-3100 with the USPLeaf showed high accuracy and precision.

Destructive methods that remove leaves from plants prevent quantification throughout the crop cycle and disrupt the assimilation and translocation of carbohydrates, another parameter of frequent interest. without destruction (KOYAMA; SMITH, 2022). Given this scenario, the use of nondestructive methods such as smart applications and mathematical equation adjustments is growing; however, there is a need for calibration and validation of these methods for each plant species to be evaluated (OLIVEIRA et al., 2019; MEIRA et al., 2020; MA et al., 2021).

Therefore, the use of different methods for quantifying leaf area in crops such as cotton is essential. Given the economic importance of this commodity worldwide, there is a need for innovative strategies, such as the use of nondestructive Baptist methods for the diagnosis of leaf area, which can improve productivity and competitiveness in the sector (AIRES DOS SANTOS et al., 2021; BATISTA et al., 2022; FERREIRA et al., 2022).

Successive evaluations of cotton leaves can be performed quickly and accurately via nondestructive methods and allometric equations based on leaf length and width (RIBEIRO et al., 2020). Evaluating leaf area is essential for understanding and assessing plant morphological characteristics (KOYAMA et al., 2022).

This study compared the accuracy and efficiency of various methods for determining cotton leaf area using both digital applications and traditional manual methods. The hypothesis to be tested is that modern nondestructive methods provide measurements as precisely as destructive manual methods do, with greater efficiency and practicality, facilitating large-scale monitoring; thus, the leaf area of the cotton plant can be quantified without removing the leaf. In view of the above scenario, the present study aimed to validate different methods for determining leaf area in four cotton cultivars.

2. MATERIAL AND METHODS

The study was conducted in a greenhouse at the Federal University of Rondonópolis (UFR), located at 16°27'50.71"S and 54°34'45.92" W, at an altitude of 227 m, from June to October 2023.

The soil used in the research was collected from the upper horizon of a soil existing in the experimental area of the UFR, classified as dystrophic Red Oxisol (TEIXEIRA et al., 2017), with the following physical and chemical attributes: Ca^{2+}, Mg^{+} and Al^{3+} = 0.5; 0.2; 0.6 cmolc dm^{-3}; pH ($CaCl_2$) = 4.3; K and P = 18.0 and 1.5 mg dm^{-3}; organic matter = 2.13%; and sand, silt and clay = 33.0, 10.0 and 57.0%, respectively (TEIXEIRA et al. 2017).

Four cotton cultivars (*Gossypium hirsutum* L.), namely, TMG44B2RF, IMA5801B2RF, FM985GLTP and BASF – FM 944GL, so that each cultivar was replicated four times.

The polyethylene terephthalate pots were filled with soil. Foundation fertilization was performed as recommended for cotton and was based on soil analysis; simple superphosphate (3.49 g), potassium chloride (3.49 g) and urea (3.49 g) were used as sources.

Planting was performed on 06/22/2023, and leaf area measurements began 30 days after planting. Leaf area was estimated weekly and ended on 10/29/2023, totaling 85 leaves per cultivar using the four methods for each leaf. Initially, random selection and identification of the leaf to be used in each pot were performed to determine leaf area using the three nondestructive methods. Next, the measured leaf was cut to apply the destructive method. The cut leaves were placed in Kraft paper bags labeled with each cultivar. All the leaves were sent to the Laboratory of the Center for Research in Production and Conservation in the Cerrado (NuPeC) for leaf area analysis using the LI-COR model 3100 apparatus, which was adopted as the standard method for validating the other methods.

To determine leaf area using the Petiole Pro application, a cell phone running Android with a camera was used. The recommendations described in the user tutorial were performed as recommended by the authors (SINGH et al., 2021). For this purpose, the area scale calibration was first performed using the reference images available in the application. The camera was subsequently positioned perpendicularly to a bench of fixed height, into which the leaves were individually inserted for image capture and automatic leaf area quantification by the application. A white background film was placed on the bench surface to improve color contrast and facilitate identification and measurement of leaf area.

To determine leaf area using the LeafArea application, procedures similar to those described above were followed. However, on each sheet, it was necessary to measure the length and enter the value in the application to indicate the measurement scale.

In addition to the methods described above, linear equations were generated to quantify leaf area (LA, in cm^2) from measurements of length (L, cm) and width (W, in cm), using Equation 1 as the correction factor. The equations were also obtained via the LI-COR model 3100, which is the standard method.

$$LA = W \times L \times f \qquad (01)$$

With the leaf area data obtained by the different methods, the calibration and validation of the methods were performed based on standard deviation (SD) to indicate how much the values are dispersed in relation to the mean; estimated standard error (ESE) to evaluate the precision of the tested methods (ALLEN et al., 1986) (Equation 2); mean square error (MSE) to assess model accuracy (Equation 3); root mean square error (RMSE) to measure the dispersion of residues between the observed values and the values estimated by the tested methods (JANSSEN et al., 1995; ALENCAR et al., 2011) (Equation 4); and mean absolute error (MAE) to evaluate the mean absolute difference between the observed and estimated values (Equation 5).

$$ESE = \sqrt{\frac{\sum_{i=1}^{N}(Y_{obse} - Y_{esti})^2}{N-1}} \qquad (02)$$

$$MSE = \sqrt{\sum_{i=1}^{N}(Y_{obse} - Y_{esti})^2} \qquad (03)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Y_{obse} - Y_{esti})^2}{N}} \qquad (04)$$

$$MAE = \frac{\sum_{i=1}^{N}|Y_{esti} - Y_{obse}|}{N} \qquad (05)$$

where: Y_{obse} is the observed value; Y_{esti} is the estimated value; and N is the number of observations (i = 1, 2..., N).

Willmott et al. (1985) (d) quantify the accuracy between the data obtained via the tested methods and the standard method (Equation 6); method efficiency (ME) is used to evaluate the performance of the tested methods in the estimation of leaf area (Equation 7); confidence index (c), proposed by Camargo; Sentelhas, (1997) combines the correlation coefficient (r) and the agreement index (d) to provide a performance indicator of the analyzed methods (Equation 8); accuracy, to verify how much a method or model can predict or estimate the actual observed values (Equation 9); and Pearson's correlation (r), to verify the degree of relationship between the variables compared (Equation 10). In addition, a figure was prepared showing the distribution of the data around the linear regression line, along with its corresponding parameters and the coefficient of determination (r^2) (Equation 11).

$$d = 1 - \left[\frac{\sum_{i=1}^{N}(Y_{esti} - Y_{obse})^2}{\sum_{i=1}^{N}(|Y_{esti} - \bar{Y}_{obse}| + |Y_{obse} - \bar{Y}_{obse}|)^2}\right] \quad (06)$$

$$ME = \frac{\sum_{i=1}^{N}(Y_{obse} - \bar{Y}_{obse})^2 - \sum_{i=1}^{N}(Y_{obse} - Y_{esti})^2}{\sum_{i=1}^{N}(Y_{obse} - \bar{Y}_{obse})^2} \quad (07)$$

$$C = d \times r \quad (08)$$

$$Accuracy = \frac{1}{n}\sum_{i=1}^{n}(Y_{obse} - Y_{esti}) \quad (09)$$

$$r = \frac{\sum_{i=1}^{N}(Y_{obse} - \bar{Y}_{obse}) \times (Y_{esti} - \bar{Y}_{esti})}{\sqrt{\sum_{i=1}^{N}(Y_{obse} - \bar{Y}_{obse})^2 \times \sum_{i=1}^{N}(Y_{obse} - \bar{Y}_{obse})^2}} \quad (10)$$

$$r^2 = \left[1 - \frac{(Y_{obse} - Y_{esti})^2}{(Y_{obse} - \bar{Y}_{mean})^2}\right] \quad (11)$$

where Y_{obse} is the observed value; Y_{esti} is the estimated value; $\bar{Y}_{obse}$ is the mean of the observed values; $\bar{Y}_{esti}$ is the mean of the estimated values; $\bar{Y}_{mean}$ is the mean of the observations; and n is the number of observations (i = 1, 2..., N).

3. RESULTS

The leaf area estimated by petiole application ranged from 0.0016 to 0.0235 m², and the leaf area estimated by LeafArea was between 0.0013 and 0.0222 m² for the cultivar FM985GLTP. The leaf area estimated by the LI-COR 3100 apparatus for the same cultivar was between 0.0019 and 0.0227 m². The statistical indicators for validating the different methods of quantifying leaf area in the cotton cultivar FM985GLTP are shown in Table 1. The estimate via the Petiole software yielded the best overall statistical indicators, with the lowest MSE (0.018 cm²), RMSE (0.002 cm²) and MAE (0.001 cm²) values and the largest r (0.976), ME (0.833), c (0.976) and d (0.999) values, which were classified as "Excellent".

The relationships between the leaf area of the cotton cultivar FM985GLTP quantified by the software Petiole and LeafArea and the measurements measured by the standard method of LI-COR 3100 are shown in Figure 1. The highest precision in the estimation of leaf area was achieved via the software Petiole (r^2 = 0.954, Figure 1A), followed by LeafArea software (r^2 = 0.641) (Figure 1B).

Table 1. Statistical indices of the performance of the methodologies for estimating the leaf area of the cotton plant FM985GLTP.
Tabela 1. Índices estatísticos de desempenho das metodologias para estimativa da área foliar de plantas de algodão cultivar FM985GLTP.

Indices	Methodologies	
	Petiole	LeafArea
SD	0.005	0.005
r	0.976	0.8
ESE	0.002	0.004
MSE	0.018	0.033
RMSE	0.002	0.004
MAE	0.001	0.002
ME	0.833	0.449
c	0.976	0.798
d	0.999	0.998
Accuracy	0.004	0.004
Performance*	Excellent	Good

SD: standard deviation; r: correlation coefficient; ESE: estimated standard error; MSE: mean square error; RMSE: root mean square error; MAE: mean absolute error; ME: method efficiency; c: confidence index; d: index of agreement. *According to Camargo and Sentelhas (1997).
DP: desvio padrão; r: coeficiente de correlação; ESE: erro padrão estimado; EMS: erro quadrático médio; RMSE: raiz do erro quadrático médio; MAE: erro absoluto médio; ME: eficiência do método; c: índice de confiança; d: índice de concordância. *De acordo com Camargo e Sentelhas (1997).

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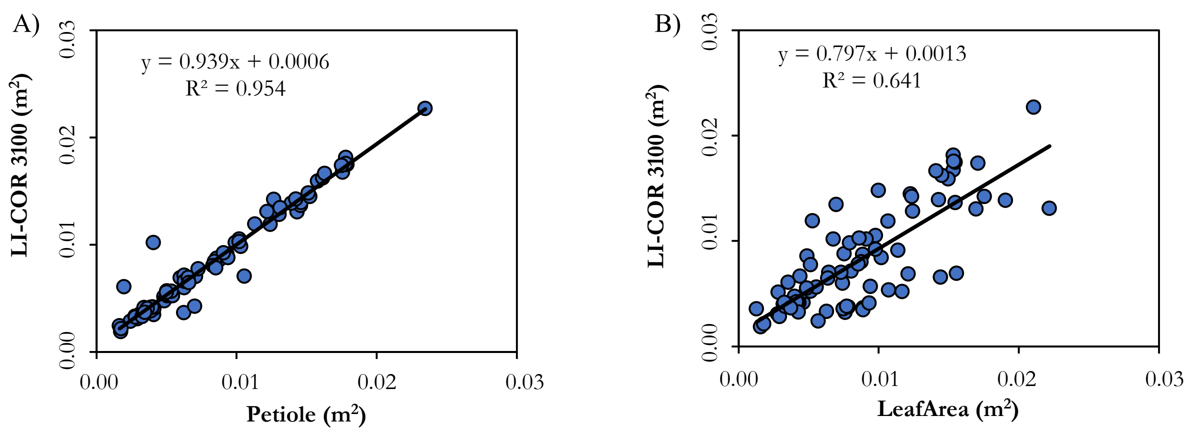

Figure 1. Leaf area of cultivar FM985GLTP estimated by the software Petiole (A) and LeafArea (B).
Figura 1. Área foliar da cultivar FM985GLTP estimada pelos softwares Petiole (A) e LeafArea (B).

The variation in leaf area was 0.0012 to 0.0148 m² and 0.0011 to 0.0163 m² for the IMA5801B2RF cultivar, as estimated via the Petiole and LeafArea applications, respectively. The leaf area estimated by LI-COR 3100 for the respective cultivar was between 0.0012 and 0.015 m². The statistical indicators used to evaluate the effectiveness of the different methods in estimating the leaf area of the cotton cultivar IMA5801B2RF are shown in Table 2.

The estimation of the leaf area via the Petiole software yielded the best overall statistical indicators, with the lowest MSE values (0.007 cm²), RMSE (0.001 cm²) and MAE (0.0004 cm²), and high values of r (0.962), ME (0.92), c (0.961) and d (0.999). On the other hand, the estimation using the LeafArea software yielded less accurate results, with high values of MSE, RMSE, and MAE and low values of r, ME, c, and d, which were classified as average.

Table 2. Statistical indices of the performance of the methodologies for estimating the leaf area of the cotton plant IMA5801B2RF.
Tabela 2. Índices estatísticos de desempenho das metodologias de estimativa da área foliar de plantas de algodão cultivar IMA5801B2RF.

Indices	Methodologies	
	Petiole	LeafArea
SD	0.003	0.003
r	0.962	0.661
ESE	0.001	0.003
MSE	0.007	0.025
RMSE	0.001	0.003
MAE	0.0004	0.001
ME	0.92	0.41
c	0.961	0.658
d	0.999	0.996
Accuracy	0.002	0.002
Performance*	Excellent	Average

SD: standard deviation; r: correlation coefficient; ESE: estimated standard error; MSE: mean square error; RMSE: root mean square error; MAE: mean absolute error; ME: method efficiency; c: confidence index; d: index of agreement. *According to Camargo and Sentelhas (1997).
DP: desvio padrão; r: coeficiente de correlação; ESE: erro padrão estimado; EMS: erro quadrático médio; RMSE: raiz do erro quadrático médio; MAE: erro absoluto médio; ME: eficiência do método; c: índice de confiança; d: índice de concordância. *De acordo com Camargo e Sentelhas (1997).

The relationships between the leaf area of the cotton cultivar IMA5801B2RF quantified via the Petiole and LeafArea software and the measurements estimated via the standard method of LI-COR 3100 are shown in Figure 2. The Petiole software (r^2 = 0.925) showed the highest precision in leaf area estimation (Figure 2A), followed by the LeafArea software with r^2 = 0.437 (Figure 2B). For cultivar TMG44B2RF, the variation in leaf area estimated by the applications Petiole and LeafArea was 0.0013 to 0.0176 m² and 0.0014 to 0.0207 m², respectively. The leaf area estimated by LI-COR 3100 ranged from 0.0014 to 0.0165 m².

Table 3 shows the statistical indicators for cultivar TMG44B2RF used to evaluate the effectiveness of the methods for estimating leaf area. In general, the methodology using the Petiole software yielded the best overall statistical indicators, with lower MSE values (0.006 cm²), RMSE values (0.001 cm²) and MAE values (0.001 cm²) and high values of r (0.988), ME (0.970), c (0.988) and d (0.999), indicating excellent performance. The methodology using LeafArea software, despite presenting lower performance, was classified as good.

Table 3. Statistical indices of the performance of the methodologies for estimating the leaf area of the cotton plant TMG44B2RF.
Tabela 3. Índices estatísticos de desempenho das metodologias de estimativa da área foliar de plantas de algodão cultivar TMG44B2RF.

Indices	Methodologies	
	Petiole	LeafArea
SD	0.004	0.004
r	0.988	0.787
ESE	0.001	0.003
MSE	0.006	0.026
RMSE	0.001	0.003
MAE	0.001	0.002
ME	0.970	0.471
c	0.988	0.785
d	0.999	0.998
Accuracy	0.003	0.003
Performance*	Excellent	Good

SD: standard deviation; r: correlation coefficient; ESE: estimated standard error; MSE: mean square error; RMSE: root mean square error; MAE: mean absolute error; ME: method efficiency; c: confidence index; d: index of agreement. *According to Camargo and Sentelhas (1997).
DP: desvio padrão; r: coeficiente de correlação; ESE: erro padrão estimado; EMS: erro quadrático médio; RMSE: raiz do erro quadrático médio; MAE: erro absoluto médio; ME: eficiência do método; c: índice de confiança; d: índice de concordância. *De acordo com Camargo e Sentelhas (1997).

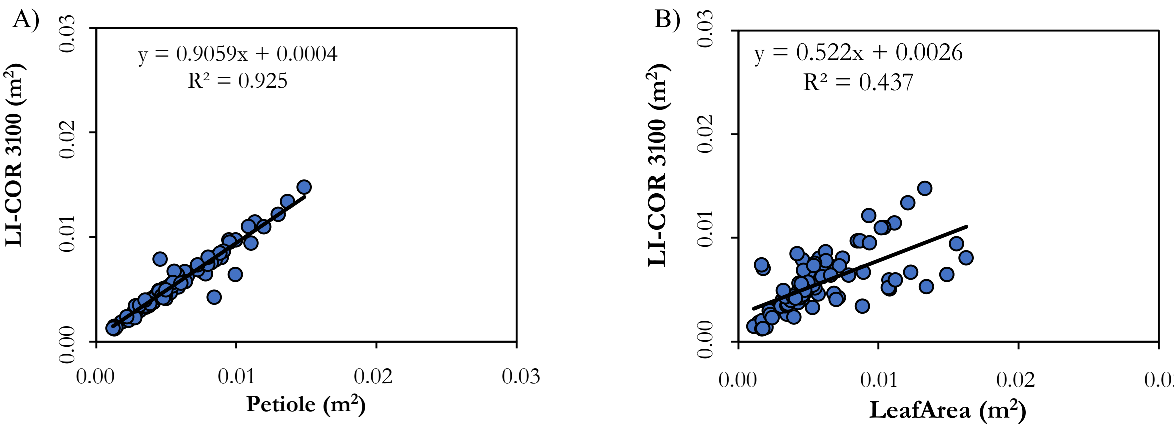

Figure 2. Leaf area of cultivar IMA5801B2RF estimated by the software Petiole (A) and LeafArea (B).
Figura 2. Área foliar da cultivar IMA5801B2RF estimada pelos softwares Petiole (A) e LeafArea (B).

Figure 3 shows the relationships between the leaf area estimation methodologies that use the Petiole and LeafArea software and the measurements estimated via the standard method of LI-COR 3100 for the cultivar TMG44B2RF. Estimation of leaf area using the Petiole software (r^2 = 0.976) yielded greater precision than the standard method (Figure 3A). On the other hand, the estimation of leaf area via the software LeafArea, with r^2 = 0.619, resulted in lower precision in the estimation of the leaf area of the cotton cultivar TMG44B2RF (Figure 3B). For cultivar BASF–

FM944GL, the leaf area estimated by the petiole application was between 0.0018 and 0.0179 m², whereas the leaf area estimated by the LeafArea was between 0.0021 and 0.0166 m². The LI-COR 3100 apparatus was used to estimate leaf area for the same cultivar, which ranged from 0.0019 to 0.0230 m². Table 4 presents the statistical indicators used to evaluate the precision and reliability of the methods for estimating the leaf area of the cotton cultivar BASF – FM 944GL. The estimation of the leaf area via the Petiole software yielded the best overall statistical indicators, with the lowest MSE values (0.026 cm²), RMSE (0.003 cm²) and MAE (0.001 cm²) and high r (0.94), ME (0.17), c (0.94) and d (0.998) values, indicating excellent performance (Table 4).

The relationships between the different methods evaluated for the estimation of leaf area with the standard method of LI-COR 3100 for the cotton cultivar BASF–FM 944GL are shown in Figure 4. The best precision for leaf area estimation was achieved with the Petiole software ($r^2 = 0.884$, Figure 4A), followed by LeafArea ($r^2 = 0.686$, Figure 4B). The variation in leaf area determined by the relationship between the length and width of the leaves was 0.0025 to 0.0312 m² for the cultivar FM985GLTP; 0.0012 and 0.0196 m² for the cultivar IMA5801B2RF; 0.0019 to 0.0221 m² for the cultivar TMG44B2RF; and 0.0027 to 0.0333 m2 for the cultivar BASF–FM944GL.

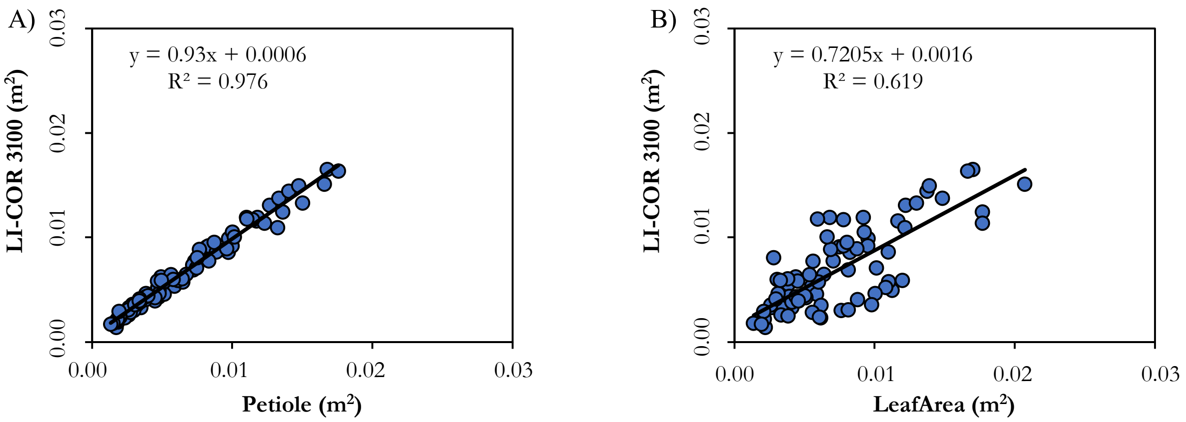

Figure 3. Leaf area of cultivar TMG44B2RF estimated by the software Petiole (A) and LeafArea (B).
Figura 3. Área foliar da cultivar TMG44B2RF estimada pelos softwares Petiole (A) e LeafArea (B).

The linear equations generated for the quantification of leaf area via measurements of the length and width of the leaves of the cotton cultivars were statistically significant according to the F test ($p \leq 0.01$), with coefficients of determination ranging between 0.893 and 0.95 and the lowest residual standard error for the equations for the determination of the leaf area of the cultivars IMA5801B2RF and TMG44B2RF (Table 5).

Table 4. Statistical indices of the performance of the methodologies for estimating the leaf area of the cotton plant BASF–FM944GL.
Tabela 4. Índices estatísticos de desempenho das metodologias para estimativa da área foliar de plantas de algodão cultivar BASF-FM944GL.

Indices	Methodologies	
	Petiole	LeafArea
SD	0.004	0.004
r	0.940	0.828
ESE	0.003	0.002
MSE	0.026	0.023
RMSE	0.003	0.002
MAE	0.001	0.002
ME	0.17	0.8
c	0.94	0.827
d	0.998	0.998
Accuracy	0.004	0.005
Performance*	Excellent	Very good

SD: standard deviation; r: correlation coefficient; ESE: estimated standard error; MSE: mean square error; RMSE: root mean square error; MAE: mean absolute error; ME: method efficiency; c: confidence index; d: index of agreement. *According to Camargo and Sentelhas (1997).
DP: desvio padrão; r: coeficiente de correlação; ESE: erro padrão estimado; EMS: erro quadrático médio; RMSE: raiz do erro quadrático médio; MAE: erro absoluto médio; ME: eficiência do método; c: índice de confiança; d: índice de concordância. *De acordo com Camargo e Sentelhas (1997).

Table 5. Parameters of the linear equations and statistical performance indices for estimating the cotton leaf area via measurements of the length and width of the leaves.
Tabela 5. Parâmetros das equações lineares e índices estatísticos de desempenho para estimar a área foliar do algodoeiro a partir de medições de largura e de comprimento foliar.

Cultivate	Equations	R²	Residual standard error
FM985	$0.7567^{**}x + 0.0004^{ns}$	0.927	0.0013
IMA5801	$0.7204^{**}x + 0.0005^{*}$	0.893	0.0009
TMG44	$0.7663^{**}x + 0.00002^{ns}$	0.950	0.0009
FM944	$0.7594^{**}x + 0.0006^{*}$	0.929	0.0012

ns, * and ** = not significant and significant until $p \leq 0.05$ and $p \leq 0.01$.
ns, * e **: não significativo e significativo, respectivamente, até $p \leq 0,05$ e $p \leq 0,01$.

4. DISCUSSION

Leaf area estimate is a fundamental parameter in the evaluation of the physiological and agronomic performance of crops, including cotton (COLAIZZI et al., 2017; LIU et al., 2021; PACHECO et al., 2020). This measure provides important information on the photosynthetic potential of plants, water-use efficiency, and light interception capacity, in addition to serving as an indicator of the crop's health status (ZHAO et al., 2020; HU et al., 2020; WU et al., 2023). In the present study, four cotton cultivars were evaluated using three methods for estimating leaf area: the Petiole and LeafArea methods and linear equations based on leaf length and width measurements obtained with the LI-COR 3100 device. The Petiole application showed the best performance in estimating leaf area for all cotton cultivars compared with the standard method LI-COR 3100, except for cultivar BASF - FM944GL, indicating its feasibility as an estimation tool;

however, manual adjustments are needed for some images. These results are essential for selecting appropriate methods for practical applications, such as the determination of leaf area in different cotton cultivars.

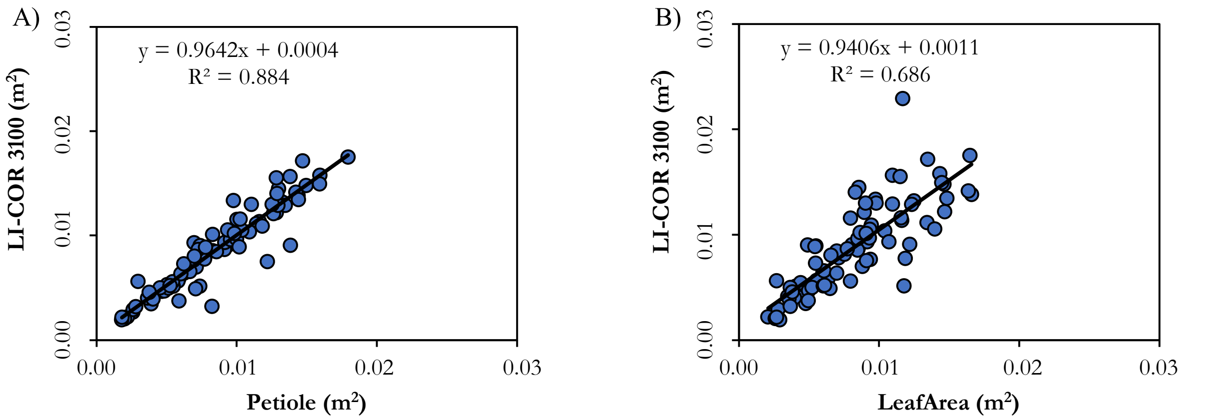

Figure 4. Leaf area of cultivar BASF–FM944GL estimated by the software Petiole (A) and LeafArea (B).
Figura 4. Área foliar da cultivar BASF-FM944GL estimada pelos softwares Petiole (A) e LeafArea (B).

The estimate of leaf area obtained with LeafArea relative to the standard method of the LI-COR 3100 showed the lowest efficiency among the cotton cultivars evaluated, indicating good performance. Among the cultivars, the estimate for IMA5801B2RF had the lowest efficiency (r^2 = 0.437), and this result may have been influenced by differences in leaf morphology across cultivars, suggesting improvements to the image recognition algorithm.

The results of this study show the advantages of applications such as Petiole and LeafArea, which are portable and easy to use and are considered promising tools under conditions of limited resources (KIZILDENIZ, 2023; SINGH et al., 2021). The ability to perform measurements directly in the field quickly and easily, without the need for sophisticated equipment, can be considered a significant advantage, especially in regions where access to laboratories and equipment such as the LI-COR 3100 is restricted (KIZILDENIZ, 2023; GUANGJIAN et al., 2019).

Recent studies using computer vision systems based on digital image processing have proposed alternative tools to traditional methods for estimating leaf area, eliminating time-consuming steps and manual measurements (MEIRA et al., 2020). Pinheiro et al. (2020), when studying the planimetric method, which is considered standard, tested the equivalence in relation to the methods of leaf dimensions - length (L) and width (W) - and to the scanner. The dimensions and scanner methods were accurate and equivalent to the planimetric method used to estimate the leaf area of the annatto.

All the equation models generated showed a significant estimate of leaf area as a function of linear measurements, demonstrating a close correlation between leaf area and linear measures of the leaves (LIMA et al., 2012). In addition, the models that used the product of the leaf dimensions yielded higher coefficients of determination than the estimates obtained from the applications for the cultivar BASF-FM944GL.

Studies by Aboukarima et al. (2015) and Ribeiro et al. (2024, 2025), who analyzed the method of estimating leaf area via the relationship between leaf length and width, reported positive results for cotton and other crops, such as castor bean and sweet potato. The equations generated for leaf area quantification, in general, showed the "f" form factor similar across the evaluated cultivars and intercept values close to zero. This difference shows that, despite differences in leaf size between the cultivars, their typical leaf shape is similar, as reported by Monteiro et al. (2005), who estimated leaf area for different cotton cultivars from leaf dimensions.

5. CONCLUSIONS

The Petiole, LeafArea and leaf length and width measurement methods enabled the determination of leaf area for cotton plants.

The Petiole method is the most effective for estimating the leaf area of the cotton cultivars TMG44B2RF, IMA5801B2RF and FM985GLTP.

The method of measuring the length and width of the leaves is the most effective in estimating the leaf area of the cotton cultivar BASF – FM 944GL.

The estimation of leaf area via the software LeafArea is less efficient than that via the Petiole methods and leaf dimension measurements.

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